Vulnerability Analysis of Power Grid Based on Multi-Agent Complex Systems

Xisong Dong, Gang Xiong(Corresponding author), Jiachen Hou, Fan Dong
State Key Laboratory of Intelligent Control and Management of Complex Systems
Institute of Automation, Chinese Academy of Sciences, Beijing, China
dongcomic04@163.com, gang.xiong@ia.ac.cn, hou.jiachen@gmail.com, fanzixi@hotmail.com

Timo R. Nyberg
BIT Research Centre, Aalto University, Aalto, Finland, timo.nyberg@tkk.fi

Abstract—**Modern power grid is a typical multi-level complex giant system. The conventional analytical methods based on reductionism can't provide sufficient guidance for its operation and management. Complex system theory, based on holism, has its specific advantages in power grid's research. But, it has some limitations. In this article, we improve complex grid by introducing new parameters which can describe the grid's characters better and using multi-agent theory. As an application, the complex power grid constructed with actual data from North China grid is constructed and its vulnerability has been simulated and analyzed under different attacks.**

Keywords-power grid; complex network; multi-agent; vulnerability; betweenness

I. INTRODUCTION

With the interconnection of regional power networks, modern power grid has already become a man-made multi-level complex giant system with the widest coverage and more and more complex structure [1]. It can improve operation efficiency, promote the optimal resource distribution. On the other hand, the increasing operation uncertainty and other elements like climatic influence and terrorist attacks give new challenges [2]. In recent years, many large-scale blackouts in different countries have happened and caused enormous social and economic losses [2].

Recently, the theory of complex networks is increasingly being exploited to tackle some sorts of complex issues, which presents a new point of view which is profitable for us to investigate the complexity of grids [3-10]. The most applications of complex network concepts to power grids are aimed at understanding the behavior of power grids both in case of accidental failures and malicious attacks.

However, there are some limitations, for example, the network statuses can only reflect the power grid's performance from the perspective of network connectivity and can't reflect the power grid's own characteristics well; the influences of various factors are not considered; the direction of current is not considered. To solve these problems, in this article, we improve the theory of complex network in two aspects: improve the description of topology structure and the parameters meaning of actual grid; introduce multi-agent theory to construct multi-agent complex network model [11-14]. The interaction among complex network and agents can realize the control target of the power grid system. At last, we construct a complex grid with actual data from North China grid multi-agent complex network and its vulnerability has been simulated and analyzed under different attacks.

The rest context is organized as follows: Section II introduces the complex network theory, the complexity of power grid and some research results on power grid; The regular construction, improvement and simulation and analysis of complex power grid's vulnerability are shown in Section III; Conclusions are drawn out in Section IV.

II. COMPLEXITY OF POWER GRID

A. Complex Grid Theory

Most of the complex systems in the world can be described in the form of complex networks. At the primary stage of complex network research, the connection topology was assumed to be completely regular, but regular net model is not sufficient to describe the networks in the real world. In 1959, Erdōs and Rényi put forward the concept of random network that greatly promoted the network research [15]. Watts and Strogatz proposed the Small-World network model in 1998 and analyzes the complexity of power grid [3]. In 1999, Barabási and Albert revealed the Scale-Free characteristic [16]. These advances overcome the shortage of random networks and revealed many characteristics of complex networks.

For a complex network G with N nodes and M edges, its parameters of the structural characteristics are as follow:

1) *Degree, Average Degree and Degree Distribution:* The degree k_i of node i is the edge's number connecting to the node. It can indicate the node's importance to some extent. The average degree <k> of the network is defined as the average value of all nodes' degree, where $<k>=\frac{\sum_{i=1}^{N}k_i}{N}$. The degree distribution $P(k)$ is defined as the probability that a randomly chosen node has degree k. $P(k)$ describes the degree distribution of all nodes, and indicates the topological characterization of systems.

This work is supported in part by NSFC 70890084, 60921061, 90920305; CAS 2F09N05, 2F09N06, 2F10E08, 2F10E10; Finnish TEKES Cloud Software Program and Finnish TEKLA R&D Fund; SFR for ROCS SEM.

2) *Shortest paths:* Among all paths, the path with smallest weight (or the least nodes) from the specific starting node to the specific end node.
3) *Distance and Average Path Length:* The distance d_{ij} between the node i and j is defined as the number of the edges which compose the shortest path connecting node i and j. If the node i and j are unconnected, then $d_{ij} = N$; The average shortest path length L is defined as the mean of geodesic lengths over all couples of nodes:
$$L = \frac{1}{N(N-1)} \sum_{ij=1, i \neq j}^{N} d_{ij}$$
4) *Network diameter:* the maximal distance between any pair of its nodes, in other words, it is the scale of the whole network.
5) *Clustering coefficient:* Assuming the degree of node i is k_i , these k_i nodes are called the node i's neighbors. E_i is defined as the actual edge among these k_i nodes. The possible maximum number of links among the node$i$'s neighboring nodes is $\frac{k_i(k_i-1)}{2}$. The clustering coefficient C_i is defined as
$$C_i = \frac{2E_i}{k_i(k_i-1)}$$
It is an important parameter to measure agglomeration degree among nodes. The clustering coefficient of the whole network is the average value of clustering coefficient of all nodes:
$$C = \frac{1}{N} \sum_{i=1}^{N} C_i$$
6) *Betweenness:* Line betweenness B_{ij} is defined as the times of being passed through the line (i,j) by the shortest paths between nodes in G. Node betweenness B_i is defined as the times of being passed through the node i by the shortest paths between nodes in G. The betweenness indicates the importance of node or line in the network. Larger betweenness of the node or line is more important, because the shortest paths are passing through them.
7) *Giant component size:* the number of nodes in the biggest connected subgraph.
8) *Network redundancy:* the shortest path length of the two nodes after removing the edges of any two nodes which are connected directly. If no path, then let it infinity.

With the development of power grids, their nodes and edges become more and more complex, and the network topological structure and main parameters have tremendous changes.

B. Complexity of Power grid

For a long time, research on power grid, people often consider natural environmental factors, equipment, manipulation factors analyzing the root, but rarely analyzing from the whole power grid characteristic. Traditional analysis method often pay attention to all parts' individual dynamic characteristics, implementation of power grid dynamic behavior analysis are through modeling simulation method to solve giant dimensional differential-algebraic equations, in essence, this method is still reductionism, it is difficult to reveal the whole system dynamic behavior characteristics. In fact, power grid topology structure is a power grid's internal and essential characteristics, once established, will produce a profound impact on power grid performance [4-6].

Power grid is one of the biggest man-made projects, which is a multi-dimensional, linear, time-varying and large-scale system. Its nonlinearity, variety, hierarchy, integrity, statistics, self-similarity, self-organization and criticality, all satisfy the general characteristics of complex systems. Power grid also has the general characteristics of complex networks: such as large-scale and dynamic behavior complexity of network nodes, sparse and structure complexity of the network connections, unpredictability and complexity of network spatial-temporal evolution, and so on [3-10].

Power Grid is a strongly large scale nonlinear dynamic system, it can be considered as a complex network constructed by power station, transformer substation and high-voltage transmission lines with different connection modes. Complex network theory and method based on holism, such as structure characteristics, transmission dynamics and synchronous' theory development, can provide a new thought and way for power grid. It can scan the whole dynamic characteristics of complex power grids from a new angle, and provide a new idea for all kinds complexity characteristics and evolution laws of complex power grid [4-10].

C. Research of the Power grid Based on Complex Network Theory

Many researchers have established their complex network models to study the actual power grid based on actual power grid's data. Recent research proves that power grid also has characteristics of complex network, summarized as follows [3-10]:

1) Power grids have often been self-organized to critical state in different evolution models;
2) Power grids generally have small world properties;
3) Power grids have different levels scale-free properties;
4) Small-world networks' specific high clustering parameters and low characteristic path length are easy to expand cascading failures' breadth and depth, which are easier to cause blackouts;
5) Small-world grid's average interruption times and sizes are more than scale-free networks;
6) Scale-free networks are easily causing small circuit breaking chains, but the losses are smaller, but lines breaking release the pressure, so as to reduce the massive outage probability. Scale-free electric power network can release pressure through small power outages.

III. Construction of Complex Power grid Based on Multi-Agent Complex Network

A. *Construction of Complex Power grid Based on Complex Network Theory*

Based on characteristics of complex network and ones of power grids, complex network topology model of power grid can be established. Concrete algorithm is as follows [4-8]:

1) The nodes of power grid models include power plants, substations and transformers, regardless ground zero points, all nodes are considered consistent with no difference;
2) High-voltage transmission lines and transformer branches are edges, and all edges are undirected;
3) Only considering the high-voltage transmission networks, not considering main connections of distribution networks, power plants and substations;
4) Topological properties of all lines are considered to be the same. The differences of the characteristic parameters of transmission lines and transmission voltage are not taken into consideration;
5) Merging the power transmission lines on the same tower, branch parallel capacitor is excluded for removing self loop and multiple edge, so the model becomes the simplified graph;
6) Only considering power transmission network, not considering the effects of distribution networks;
7) Ignoring the physical structures of different transmission lines and the differences of electric parameters, so the model becomes undirected graph.

B. *Research of the Power grid Based on multi-agent Complex Network*

Introducing physical parameters to describe power grid characteristics, the characteristics of the power grid itself can be reflected in complex network models. However, the existing network statuses can only reflect the power grid's performance from the perspective of network connectivity and can't reflect the power grid's own characteristics well. For example, the difference of nodes are not considered, node might be power stations, substations or transformers, might also be other high-voltage load; various factors such as political, society, economy, geography, environment, weather, equipment and human effect's influences are not considered, which are dynamic, complicated, variable, and may produce more influence than the power grid itself.

The characteristics of the power grid itself can be reflected in complex network models by introducing physical parameters. However, the existing network statuses can only reflect the power grid's performance from the perspective of network connectivity and can't reflect the power grid's own characteristics well. For example, the difference of nodes are not considered, node might be power stations, substations, transformers, or other high-voltage load; The influences of various factors, such as political, society, economy, geography, environment, weather, equipment and human effect's which are dynamic, complicated, variable, and may produce more influence than the power grid itself, are not considered.

In order to solve the above problems, there are two aspects of work to do. On the one hand, the description of topology structure and the parameters meaning of actual power grid should be improved. For example, some new parameters are introduced to describe the characteristics of power grid, such as net-ability, path redundancy, survivability, entropic degree and transmission betweenness etc.; and the complex network model can be improved to become the weighted directed graph so that current transfer can be calculated better [10]. On the other hand, agent theory is introduced to construct multi-agent complex network model. Agent theory is the newest development in the field of artificial intelligence. The agent, with its responsiveness, initiation and sociality, can apperceive its environment and take independent action to achieve its design targets [11-14].

The agent structure is shown in Fig. 1. The relationships among an agent's all parts are as following:

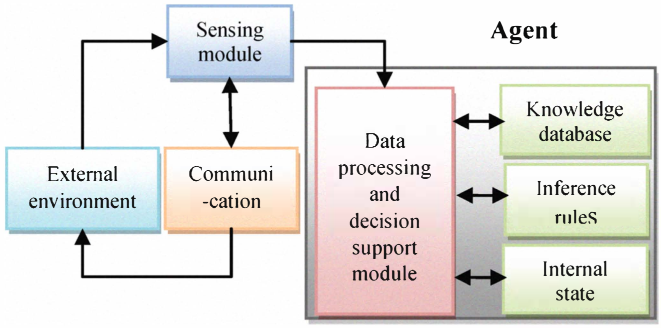

Figure 1. The structure of Agent of complex power grid

1) Sensing module detects the information transmitted from external environment;
2) Data processing and decision support module receive the information from Sensing module, and then makes its decision–making plan by combing the information with agent's own internal state, knowledge base and inference rules.
3) Communication Modules can transfer the decision -making plan to affect the external environment, and directly receive the information from the sensing modules, simply process the execution information and apply it into external environment.

Compared with traditional modeling and simulation, agent-based modeling and simulation can not only provide more realistic modeling method, but also get the emerging characteristics of complex system from micro to macro behaviors, and reveal the inner micro mechanism of complex system's macroscopic characteristics. Complex network theory and agent-based simulation can provide more satisfactory reality, more effective modeling means and guidance theory to describe and study complex power grid, which can greatly enhance the capacities of understanding, research and control of complex power grid. Therefore, complex power grid is established according to multi-agent complex network theory, which integrates the advantages of agent theory and complex network, and so can reflect the essential characteristics of actual power grid.

The construction of Multi-agent complex power grid:

1) Construct the regular complex network (See Part A Section III);
2) The nodes of network are agents;
3) The network is directed;
4) Simplify the structure of Agent, because the number of a grid's nodes is very large;
5) The agents of this network can only communicate to the near nodes;
6) Limit the communication in the connection and direction of node

C. *Validation of* Multi-agent *Complex Power grid*

The complex power grid model of North China power grid is built according to the methods of improved complex network and multi-agent theory. The model is built by the actual data, represents the power grid as a network of 2556 nodes and 2892 edges (See Fig. 2). The vulnerability indexes are attained, and then the vulnerability of the North China power grid under different attack modes is analyzed in this section (See Fig. 3).

In order to test the electric betweenness' status, three different attack modes were combined to launch a chain of attacks. To prove high electric betweenness circuit is very fragile under attack. The modes are shown below:

1) Random attacks

Delete some nodes or lines;

2) Static attacks

Range the circuits by electric betweenness of lines or nodes, let every line failures happens in sequence from large to small.

3) Dynamic attacks

Similar to static attack, but recalculate the rest of nodes and lines' betweenness and degrees after each attacks.

Figure 2. North China power grid

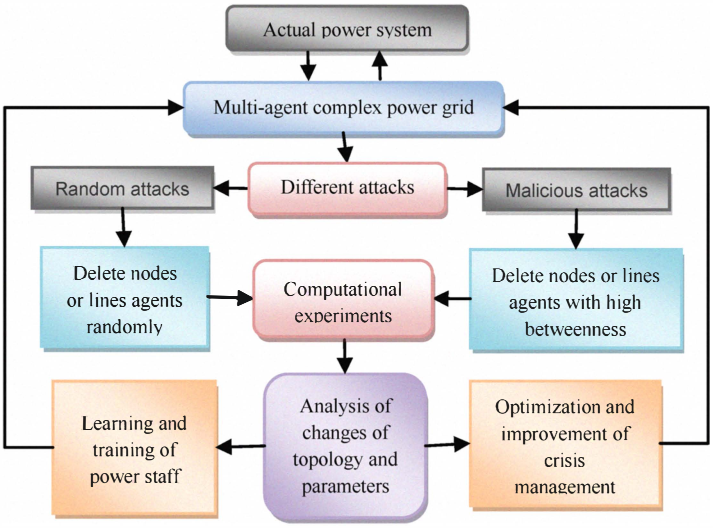

Figure 3. Different attack of complex power grid

The complex power grid's efficiency after the random, static and dynamic attacks is shown in Fig. 7, and following conclusions can be drawn:

1) As far as actual power grid's operation, transmission lines and substations at 500kV play the roles of transmitting and distributing high power capacity, they are much more important than other substations. It is also validated that the proposed vulnerability indexes meet with the actual power grid's operation condition.

2) It should be noted that the system is very robust against random attacks. Under random attacks, the curve changes slowly, which indicate that the power grid has stronger anti-attack ability.

3) Under dynamic and random attacks, those nodes and lines with a high betweenness weight are removed, the network performance decreases drastically to about 20% and 40% of the performance after the attacks on systems. This shows that these nodes and lines with higher betweenness weight assure the convexity, but at the same time, accelerate the faults' spread if they are cut off. Cascading failures scale will be enlarged rapidly if failures occur at these nodes and lines, sometimes this kind of failures can result in large scale blackout eventually.

4) Both after under dynamic and random attacks, the network performance after the attack to lines decreases more drastically than nodes. In other words, the lines with high betweeness are sensitive than the same nodes which implies that lines may be important in the security of power grid.

In summary, the system is very robust against random attacks. But, when the nodes or lines with highest betweenness are maliciously attacked, the system will suffer worse destruction than random attack's damage. These nodes and lines' fault chain reaction should be avoided to decrease the occurrence probability of massive chain reaction. The topology structures of power grid have important influence on its vulnerability; high betweenness paths and high betweenness nodes have important influence on the system's vulnerability. Therefore, in order to increase the whole gird's reliability, the key parts, especially high betweenness lines, must be enhanced to avoid the fault chain reaction of these parts, then to decrease the occurrence probability of massive accidents.

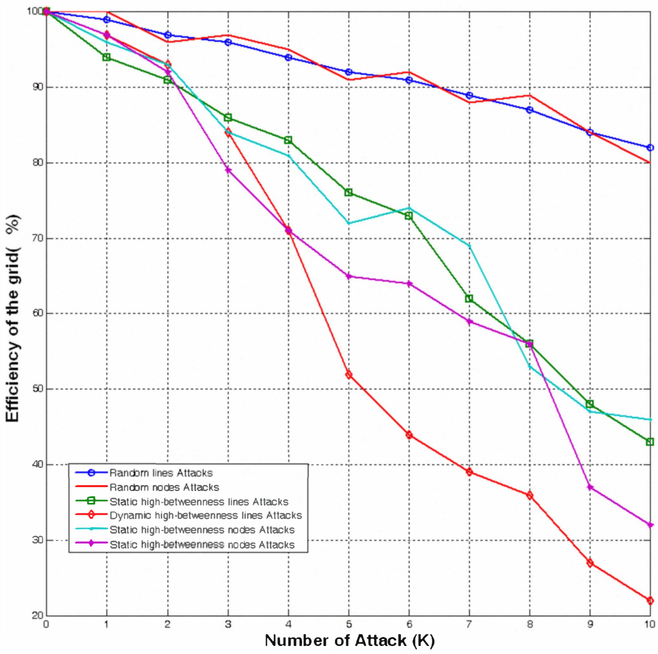

Figure 4. The efficiency of the complex power grid of North China grid under different attacks

IV. CONCLUSION

Modern power grid is a typical multi-level complex giant system. The conventional analytical methods can't provide sufficient guidance for its operation and management.

Complex system theory based on holism and, has its specific advantages in the research on power grid. But, it has many limitations. In this article, we improve complex grid by introducing new parameters which can describe the grid's characters and using multi-agent. As an application, the complex power grid constructed with actual data from North China power grid is simulated and analyzed under different attacks. The analytical results show that the power grid is very robust against random attacks; but, when the nodes or lines with highest betweenness are maliciously attacked, the system will suffer worse destruction than random attack's damage.

REFERENCES

[1] F. Y. Wang, J. Zhao and S. X. Lun, "Artificial power systems for the operation and management of complex power grids," Southern Power System Technology, Vol. 2, No.3, pp.1-6, 2008.

[2] W. W. Zhao, "Research on analyzing model and prevention & emergency system for power system blackouts," D.S. thesis, North China Electric Power University, Beijing, China, 2009.

[3] D. J. Watts and S. H. Strogatz, "Collective dynamics of 'small-world' networks." Nature, Vol.393, No.6684, pp. 440-442, 1998.

[4] M. Rosas-Casals, "Power grids as complex networks: topology and fragility," Complexity in Engineering, pp. 21-26, 2010.

[5] G. H. Zhang, C. Wang, J. H. Zhang, J. Y. Yang, Y. Zhang and M. Y. Duan, "Vulnerability assessment of bulk power grid based on complex network theory," 3rd International Conference on Electric Utility Deregulation and Restructuring and Power Technologies, pp.1554-1558, 2008.

[6] W. J. Bai, T. Zhou, Z. Q. Fu, Y. H. Chen, X. Wu and B. H. Wang, "Electric power grids and blackouts in perspective of complex networks," International Conference on Communications, Circuits and Systems Proceedings, Vol. 4, pp. 2687-2691, 2006.

[7] X. H. Yu, A. Dwivedi and P. Sokolowski, "On complex network approach for fault detection in power grids," IEEE International Conference on Control and Automation, pp.13-16, 2009.

[8] X. G. Chen, K. Sun, Y. J. Cao and S. B. Wang, "Identification of vulnerable lines in power grid based on complex network theory," IEEE Power Engineering Society General Meeting, pp.1-6, 2007.

[9] S. Z. Xu, H. Zhou, C. X. Li and X. M. Yang, "Vulnerability assessment of power grid based on complex network theory," Asia-Pacific Power and Energy Engineering Conference, pp.1-4, 2009.

[10] Z. B. Wei and J. Y. Liu, "Research on the electric power grid vulnerability under the directed-weighted topological model based on Complex Network Theory," International Conference on Mechanic Automation and Control Engineering, pp. 3927-3930, 2010.

[11] Q. L. Pang, H. H. Gao and M. J. Xiang, "Multi-agent based fault location algorithm for smart distribution grid," 10th IET International Conference on Developments in Power System Protection, pp.1-5, 2010.

[12] M. Pipattanasomporn, H. Feroze and S. Rahman, "Multi-agent systems in a distributed smart grid: Design and implementation," IEEE/PES Power Systems Conference and Exposition, pp. 1-8, 2009.

[13] D. Rui and D. Geert, "Multi-agent model and interoperability of a market mechanism of the Smart Grids," Network Operations and Management Symposium Workshops , IEEE/IFIP, pp. 312-315, 2010.

[14] F. Y. Wang, "Agent-Based Control for Networked Traffic Management Systems", IEEE Intelligent Systems, vol.20, no.5, pp.92-96, 2005.

[15] P. Erdos and A. Renyi, "On the evolution of random graphs," Publications of the Mathematical Institute of the Hungarian Academy of Sciences, no. 5, pp.17-61, 1960.

[16] A. Barabási and R. Albert, "Emergence of scaling in random networks," Science, Vol. 286(5439), pp. 509-12 ,1999.